

dissolving unreactive metals, such as copper, in strong acids. Using a mixture of nitric and hydrochloric acids, he prepared a substance called *aqua regia*, so strong that it was able to dissolve the gold medals into a colourless solution.

When the Nazis came, all they found was a scary-looking bottle of acid on the dusty old shelf. They left empty-handed. After the war, by adding chemicals to the solution, Hevesy was able to precipitate out the gold and the Nobel prize foundation melted it down and re-moulded the medals for the two chemists. They had their medals back, and the Nazi's had been duped by clever chemistry!

Design-Based Science

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Abstract

Design-Based Science (DBS) is a pedagogy in which the goal of designing an artifact contextualizes all curricular activities. Design is viewed as a vehicle through which scientific knowledge can be constructed. DBS units are structured around a learning cycle based on models of design and a socio-constructivist perspective of learning.

We are born designers. When children think about ways to connect a wagon to a tricycle in order to pull their friends behind them, they are designing. When you consider how to organize your desk so that everything you need will be easily accessible, you are designing. We all purposefully use tools and materials in adapting our surroundings to suit our needs. Design-Based Science (DBS) (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004) is a science pedagogy that aims to help students construct scientific understanding by building on this natural and intuitive experience with design. The design of artefacts in DBS is not viewed as a culminating experience, where the students attempt to apply scientific knowledge, constructed in the traditional manner of focusing on well-defined problems, to a real-world problem. Rather, the design experiences lie at the heart of DBS. All scientific knowledge is constructed in the context of designing artifacts.

The Design Process

Everyday design is not the same activity as Design (capital D) in which professional designers engage. The two differ in their level of formalization: while everyday design is usually spontaneous and intuitive, Design usually includes many explicit stages and criteria for determining whether the outcomes of the Design process are acceptable. Everyday designers often err in their decisions and considerations, whereas the Design process attempts to minimize the chances that Designers will do so as well. The Design process has much in common with scientific inquiry, as demonstrated in Table 1.

It is often difficult to engage students, especially younger students, in authentic scientific inquiry. By authentic, I mean that the classroom activities are both good simulations of scientific inquiry as experienced by professional scientists and something that the students can relate to on an intuitive level. However, by engaging students in Design, DBS does just that. Students can gain experience in DBS contexts that will support their forays into scientific inquiry, because they will already be knowledgeable and well-acquainted with many of the aspects of scientific inquiry.

Table 1
Commonalities Between the Design Process and Scientific Inquiry

Design process	NSES ^a inquiry standards
Identify and define the problem	Pose questions
Gather and analyze information	Review what is already known
Determine performance criteria for successful solutions	Make predictions
Generate alternative solutions and build prototypes	Plan investigations
Implement choices	Consider alternative explanations
	Make observations
	Gather, analyze, and interpret data
Evaluate outcomes	Propose answers and explanations
	Communicate results

^aNational Research Council (1996).

As examples of the DBS pedagogy, consider three ninth-grade units that were developed at the University of Michigan. All three units are standards-based (National Research Council, 1996) and structured around design problems chosen to be interesting and challenging to the students. In the first of these DBS units, called “How do I Design a Structure for Extreme Environments?” the goal is to design and build a model house that can withstand extreme environmental conditions. In the second unit, “How do I Design a Battery That is Better for the Environment?” the goal is to design and build a wet cell that makes use of nontoxic materials. In the third unit, “How do I Design a Cellular Phone That is Safer to Use?” the goal is to design a cellular phone that minimizes potential radiation and sound hazards without compromising customer appeal. Each unit begins with the presentation of a design specification that includes the requirements the students’ models are expected to fulfill. Please see Appendix A for an example. Thus, the students know in advance what the unit is about and what is expected of them.

A Design Learning Cycle

Since the goal of DBS is not to foster learning about Design, but to use Design as a vehicle for learning science, it is necessary to provide a scaffold that allows the students to engage in Design without needing to explicitly instruct them on the Design process. This is achieved by organizing each DBS unit around multiple applications of the learning cycle shown in Figure 1.

The structure of the learning cycle is based on a stepwise description of the Design process and a social constructivist perspective of learning. In order to acquaint the students with the stages in the Design process, each cycle is usually completed in an orderly manner. However, as is to be expected for a nonlinear process, there are cases that short-circuit steps in the cycle, or have steps executed out of order.

Each cycle, in each of these DBS units, focuses on a different aspect of the unit’s design problem. The “How do I Design a Structure for Extreme Environments?” unit is composed of five cycles, dealing with weather conditions, technical drawings, different sources of loads, shape and structural integrity, and thermal insulation. The “How do I Design a Battery that is Better for the Environment?” unit is composed of four cycles, dealing with toxic materials and their disposal, different types of batteries, the materials from which they are made, and the health hazards related to these materials, how batteries decay and how to measure this, and electrochemistry. The “How do I Design a Cellular Phone that is Safer to Use?” unit is composed of five cycles, dealing with the potential hazards of EM radiation, the historic form and function development in telephones, general wave characteristics, sound waves, and EM waves.

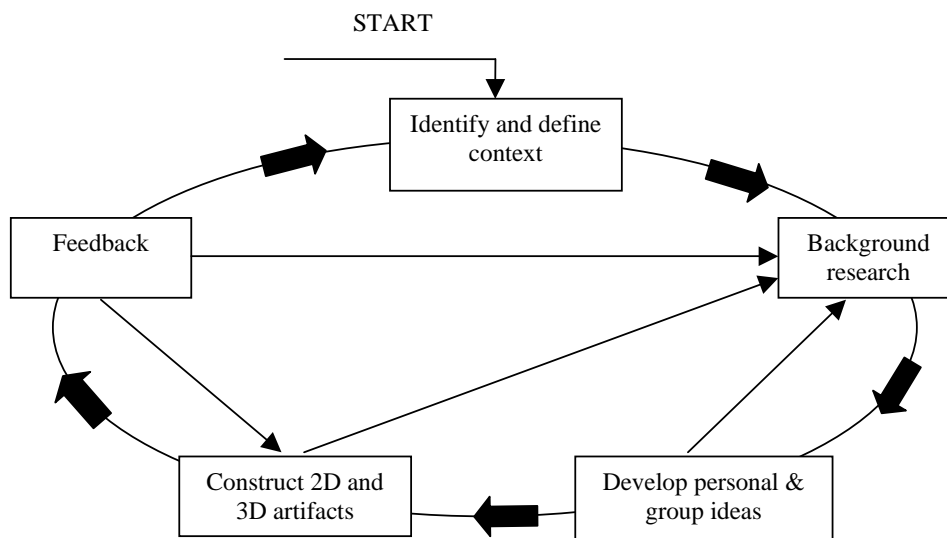


Figure 1. The Design-Based Science learning cycle.

In each cycle, students conceive, design, construct, and modify models of structures for extreme environments, batteries that make use of safe materials, or cell phones that pose less of a potential hazard to their users. During the unit enactments, a poster of the learning cycle is displayed on the wall at the front of the classroom. The learning cycle is presented briefly to the students near the start of the first cycle of each unit, and then it is mentioned at the start of each lesson, with the teacher pointing out how the day's planned activities fit in the cycle.

Steps of the Learning Cycle

I now elaborate on the various steps in each learning cycle, giving examples drawn from the Extreme Structures unit.

Step 1: Identify and define context. Each cycle begins by setting the context for the cycle's focus. Context supplies significance for the tasks the students will be facing and provides starting points for things the students can immediately begin to investigate. For instance, the first cycle in the Extreme Structures unit begins by showing the students films depicting an arctic blizzard and a Sahara sandstorm. This leads directly to a research activity in which the students inquire into the weather conditions (temperature, precipitation, and wind speed) typical of these two different extreme environments. It is important to grapple with a subject in more than one context. By teaching a subject in multiple contexts, there is a greater chance that students will succeed in constructing a more flexible knowledge representation and enhanced ability to apply the knowledge in new contexts. DBS units present each concept in at least two different contexts. As another example, thermal insulation is discussed in the context of a house, an ice cube in a tin can, and a cup of hot chocolate.

Step 2: Background research. Background research can be in the form of benchmark lessons that include the teacher presenting new scientific concepts, the reading of selected materials, searching and gathering relevant information, the sharing on a whiteboard of data collected in group experiments and then collectively analyzing the complete database, teacher-led demonstrations,

computer-based simulations of relevant phenomena, and a virtual expedition to examine appropriate primary sources.

As an example, working in groups of four in a jigsaw activity, students in the Extreme Structures unit investigate the dependency of a beam's vertical deflection on the mass of a weight being hung from its center and on the distance between the beam's two support points. Each group is given a yardstick (beam), which they support between two tables (pillars), and every group places their tables at a different distance apart (different spans). They then hang a series of weights from the center of the yardstick, measure the yardstick's vertical deflection for each weight, and create a graph of the yardstick's deflection against hung mass. The teacher prepares a table on the whiteboard, with each row representing a different span and each column a different mass. The cells in the table represent the various vertical deflections. A representative from each group fills out the cells in a particular row according to the group's measurements. The teacher also prepares a blank graph with axes representing deflection and hung mass. Using different colored markers, representatives from each group draw a different deflection versus mass curve. After discussing the results, explaining how span is a varying parameter in this graph, and clarifying any misunderstandings, the teacher shows how the same results can be graphed differently as span versus hung mass, with deflection as the varying parameter. Thus, for a known mass, students can select the span that will give a desired deflection. The teacher explains that this is how an architect would approach the problem and how they can use what they've learned in the investigation in designing their structures; that is, by knowing the mass a beam has to support and knowing the maximum vertical deflection the beam (roof) can tolerate, you can determine the maximum distance between the pillars supporting the beam.

Step 3: Develop personal and group ideas. Activities are carried out on four levels: individual, pairs, groups of four, and the entire class. Following the background research stage, every student comes up with his or her own design solution, be it a method to prevent the roof of a structure from sagging, or a scheme for increasing the thermal insulation of a structure. Group problem solving that involves open-exchange and elaborate discussion among group members can enhance student learning. Thus, the students present their solutions to their group members and the group decides which of the four suggested solutions they prefer, or perhaps they decide to combine the solutions in some manner, and they write a justification for their decision. By providing an opportunity for the students to contrast their own thinking with that of others, the students begin to develop a critical appreciation of the different aspects of the problem that will assist them in learning new and related information.

Step 4: Construct 2D and 3D artifacts. In the next stage, each design team splits into pairs, with each pair constructing a model, or modifying an existing model, based upon the design solution their design team decided on in the former stage. The construction work is done in pairs, rather than in teams, in order to provide each student with as much hands-on interaction as possible with the various aspects of their models. This is the stage when the students' ideas are concretized. Concepts and notions that may have been vague and unspecific need to be reevaluated and reorganized in order to allow them to guide the development of a material artifact. The students realize the appropriateness and reasonableness of some of their ideas, and the unsuitability and impracticality of others, opening the way for some conceptual models to become entrenched and others to be replaced.

After each pair has constructed or modified a model, they rejoin their design team members to discuss and compare their models. They decide which model is superior and then prepare a document to justify it. The justification is based on the document they wrote in their design teams

in the former stage and the experience they gained while constructing, modifying, and comparing their model.

Since every team is divided into two pairs, and each pair builds a model according to a solution agreed upon by the entire design team, the two models built by the two pairs should bear a great resemblance. However, since the students' ideas and understandings are themselves modified while constructing the physical models, there is also some variance between the two models. Close inspection and analysis of these models can provide the teacher a window to the students' understandings. This inspection is carried out in the next step.

Step 5: Feedback. Ongoing formative assessment provides students with opportunities to revise and improve their understanding, thus supporting their learning. Therefore, students' models are subjected to physical tests whenever possible, and they are presented several times to the entire class in a pin-up session in which the models are laid out or hung up and the entire class moves from model to model, listening to the student-designers' descriptions and the teacher's comments, and offering their own critique.

Not every model built is assessed. Every design team builds two models and decides which one they think is superior. In order to maintain a reasonable limit to the time spent on the feedback sessions, only the select models are critiqued or tested. When subjecting their model houses to physical tests, such as determining whether they provide sufficient thermal insulation, the students are not only testing their models to see whether they meet the specification requirements, but they are also learning about testing procedures in general. They learn how the physical characteristic being evaluated determines what type of data needs to be measured, what other characteristics need to be controlled, how to organize, and how to analyze the data. Likewise, while receiving and giving feedback in a pin-up session, they are not only learning about the pluses and minuses of their own model, but learning how to present their ideas clearly and simply so that others may understand. They are also learning from the comments given to their peers' models, which may reveal ideas that they didn't think of.

Enactments and Outcomes

All three units were enacted in three classes in the sole high school of a small industrial town located near Detroit, Michigan. All 92 students who participated in the enactments came from blue-collar families, and many were entitled to free or reduced-price lunch. During the enactment, there was a 16% turnover in the student population. The teacher had 3 years experience teaching, but only one term of doing any inquiry-based instruction.

The students' understanding of the science content in each unit was assessed by identical pre- and post-tests. There were three different tests, one for each unit. The tests comprised multiple-choice and open-ended items that probed for different levels of understanding using low, medium, and high-cognitive-demand items. The tests focused on the specific science content that was addressed in each unit, in contexts similar to those used in each unit. Although it was originally intended to use the tests only for research purposes, the teacher chose to use them as the final exam for each unit. The results are shown in Table 2.

High and low achievers were defined as those students who scored above and below the median in a pre-test, respectively. The mean gains for both groups were calculated. The results show that learning gains occurred for both high and low achievers. Other analyses showed that there were probably ceiling effects that limited the gains of the high achievers. The effect size is the ratio of

the mean gain to the standard deviation. An effect size greater than 0.8 is generally considered to indicate that significant learning occurred.

Table 2
Pre- and Post-Test Results

Unit	Pre-test median	Mean gain		Effect size
		Low achievers	High achievers	
Structures	7.9/23	8.3	5.3	2.1
Batteries	6.7/22	6.4	3.7	1.9
Cellphones	3.0/21	8.0	6.4	2.7

Student learning was also assessed through artifact analysis. Figure 2 shows a model structure built by a group of students toward the end of the Extreme Structures unit.

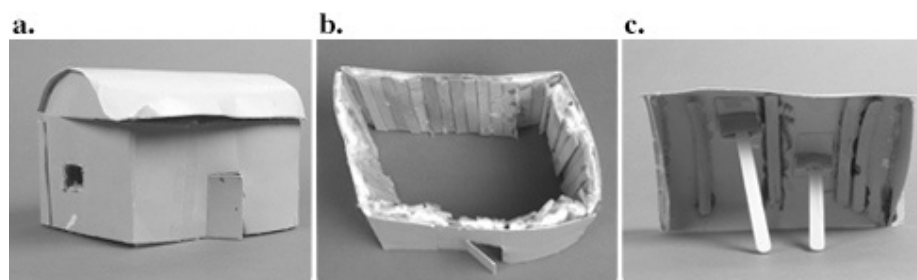


Figure 2. An example of an Extreme Structures model. Part a shows the complete model, part b the construction of the walls, and part c the construction of the roof and its supports.

The model is made of construction paper, Popsicle sticks, and cotton. The structure is a parallelepiped, with an arched roof to keep snow and sand from piling on it (reasoning given by the students). Initially, the students used only four bent beams to support the roof, but when weights were placed on the model, the roof started to cave in (the beams did not lie on top of the vertical walls), so rather than adding other horizontal beams that would be perpendicular to those shown, they added two pillars near the center of the structure. The walls are made of vertically placed Popsicle sticks and construction paper, with cotton between them as thermal insulation. When placed inside an ice chest for 1 hour, the air temperature inside the structure decreased by only 3°C, even though the initial temperature difference between the air inside and outside the structure was almost 20°C. Why the sticks were placed on the inside rather than the outside is unclear. The window and door were placed on different walls to allow a breeze through the structure. The door can open only outwards, so it remains stuck when there is snow or sand piled on the ground. There is no floor, nor is there a description of how the structure would be held in place. The students stated that the outside walls should be painted either white or black, depending whether the user wanted to reflect light (desert conditions) or absorb it (arctic conditions).

Caveat

Like every science pedagogy, DBS too has its drawbacks:

- A. There is a multitude of design solutions that can meet any given specification; some may be better and some worse, but many can be acceptable responses. It is difficult for the teacher to know in advance what form the design solution of a group will take. The existence of this

multitude of “correct” responses may make it difficult for many teachers to use DBS units, as it requires them to relinquish their traditional role of knowledge imparters.

- B. Design is not a convenient context for learning about the microscopic world.
- C. In some sense, the design specification in DBS can be viewed as setting up a competition in which the students compete, not with each other, but with the specification. A design goal like “Can you design a cellphone that is safer to use?” sets a challenge, daring the students to test their skills and knowledge and see if they can design a cellphone that fulfills all of the specification’s requirements. Like ownership, a sense of challenge can be a powerful motivator. However, it can also deter some students.

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Appendix A



Structures
Project

Extreme Structure Design Specifications

Learning Set One: Introducing the Driving Question

The continuing quest for oil, the effort necessary to study a new species, or the desire to be the first explorer in an unknown terrain are causing scientists to venture into environments that are more extreme than what we experience everyday. Research is being done in the deserts of Africa and among the plains of Antarctica. Under normal conditions, researchers can work in these environments. However, under extreme conditions like blizzards or sandstorms, these environments become too hostile for unsheltered human survival.

You goal is to design and build a model of a structure that can provide protection in the harsh weather conditions of different extreme environments.

The requirements for the survival structure are that it:

- ✓ must function in two extreme environmental conditions: arctic blizzards and desert sandstorms.
- ✓ needs to withstand the static and dynamic forces caused by the climatic conditions of the environment it is in. **Antarctica** has high winds that carry snow and the **Desert** has high winds with sand.
- ✓ needs to maintain an internal temperature between 0°C and 30°C for at least 1 hour, without internal heating or cooling, even though it may be subjected to intense sunlight and the temperature outside may be as low as -20°C and as high as 40°C.
- ✓ needs to fit within a space of 5 x 4 x 2.5 meters.
- ✓ needs a door for entry and exit and a window to view the outside.

Each designer will need to do **research** to gather specific facts about the:

- climatic conditions,
- engineering principles behind dead and live forces,
- best aerodynamic shapes for the structures, and
- best way to insulate a structure to maintain a constant temperature.

At the end of the unit, each designer will produce a:

- 1:50 **scale model** of the structure.
- **concept diagram** and **scale drawing** of the structure.
- **written description** of the testing process, and a **written review** of the testing results to support the safety of your structure.

Demonstration

While the activities in this section of *SER* have been designated demonstrations, some might easily be structured as hands-on student learning experiences. Although some sample lesson sequences may be included, the notes provided both here and in the following *Student Experiments* section are meant to act primarily as stimuli for classroom activities and to provide teachers with background information, so please modify any sample pedagogy as you see fit.

The Edible Candle

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On pages 35-36 of this volume of *SER*, I referred to the use of a discrepant event, such as the Edible Candle demonstration, at the beginning of class as a strategy for gaining immediate student attention. Following is a lesson plan for that demonstration, which requires observation, inference, and the generation of hypotheses.

Safety: Students should not handle the flaming items, nor try to duplicate this activity on their own. The teachers should model safety by using safety glasses. Have water handy.

Needed. Wax candles of varying colors, heights, and textures, large potato, apple corer (or piece of metal pipe), knife, large nut (e.g., a Brazil or almond nut), 10 mL lemon juice, plastic sandwich bag, source of fire (e.g., candle lighter or matches), paper towels, safety glasses, and container of water (for safety).

Advance preparation. Shortly before class, use the apple corer to cut out a cylindrical, candle-shaped section of the potato. Trim the ends of the potato with a knife so it is flat and stands up. Cover the potato “candle” with lemon juice by soaking briefly in the sandwich bag. This prevents oxidation and improves the taste somewhat. Carve a piece of the nut into a “wick,” and insert it into the top of the candle. You may need to use the knife to form a slit, in the top of the potato candle, to hold the wick.

Invitation. Just before class starts, line up a set of about six candles and include your potato candle in the lineup. When class is due to start, have students take out a sheet of paper (or make mental